MEASURING ACCURACY OF IMPULSE MEASURING CIRCUITS

For some time now the IEC has been working toward defining acceptable criteria for impulse measuring apparatus based on the concept of response time. Figure 1 illustrates the basic definition of response time. The concept of response time is a direct extension of the convolution or the Superposition Integral Theorem which states

$$H(t) = \int_{0}^{t} F(\tau)\,\frac{d}{dt}\left[\phi\,(t-\tau)\right] d\tau$$

where

$H(t)$ = response to the input
$F(\tau)$ = arbitrary input
$\phi(\tau)$ = response of the system to a step function

The Superposition Integral Theorem thus states that if the response of the system is known for a step function, the response of that system may be determined for any other arbitrary input function. The concept of the Superposition Integral is a purely mathematical concept and is thus divorced from any physical considerations of actual physical measurement apparatus.

When dealing with impulse voltage dividers (or other impulse measurement apparatus or in fact any other physical apparatus), the concepts of the Superposition Integral are still applicable. However, the usage of these concepts is not always correct. In one important matter, the matter of impedance of the test source used to generate a step function from which the response of an impulse divider is measured, the usage of the Superposition Integral by many authors, the present writer included, has been incorrect. When the foundation concepts of the Superposition Integral Theorem are used incorrectly, it is not surprising that the superstructure built upon these foundations may get shaky. Such is the present case regarding the entire concept of response time as it is used in the IEC.

Basically, the problem arises from the way in which the step response is normally determined in laboratories. This method of determination is shown on Figures 2A and 2B. In Figure 2A, DC voltage is impressed on the divider system from a power supply. The output of this power supply is then shorted to ground through a switch, usually a switch having mercury-wetted contacts to avoid secondary problems of contact bounce. Typically, a resistor is inserted between the divider under test and the power supply to prevent placing a damaging short circuit on the power supply. During such a measurement the line lead of the divider under test is extended and brought down to the ground plane adjacent to the switch. When the switch is closed, the rapid collapse of voltage at the switch contacts takes place almost instantaneously and the divider is then subjected to a step function change in the applied voltage from which the measured output of the divider constitutes the step function response. The voltage divider in this sense is taken in the broad sense, meaning the impulse divider proper, the associated high voltage measurement lead, and the output leads and indicating device from the divider. Since the test is carried out at relatively low voltage, it is generally necessary to observe the divider response with an oscilloscope having an internal signal amplifier. The only basic requirement of this amplifier and oscilloscope is that its response time be much faster than the response time of the divider under test. Most well-equipped laboratories these days have such oscilloscopes.

Alternatively a spark gap (pressurized for fast switching) is used to chop an applied impulse voltage. With such a gap the divider output voltage is high enough to observe on an oscilloscope without amplification.

Having once determined the step function response, the resulting display of that response may be analyzed to see if the response time meets the criteria specified in the IEC documents. If these requirements are met, the divider is then used in actual high voltage impulse circuits. What most of us have overlooked, however, is that the response of a divider in an impulse generator circuit is not the same as the response of a divider to a step voltage generator. It is one thing to calculate the response of System A if the response of System A to a step voltage is known. It is quite another entirely to attempt to determine the response of System A if only the response of System B to a step voltage is known. Another way of phrasing this is that the system we are using for our actual high voltage measurements is not the same system that we have tested for compliance with the requirements of IEC.

What brought this subject to the fore is that many impulse divider systems, when tested with step function input waves according to Figure 2, exhibit an oscillatory type of response. Considering the mathematical fiction called the Superposition Integral, it can be demonstrated that serious measurement errors can be made if such an oscillatory system is used to measure certain hypothetical impulse waves, impulse waves typically not truly encountered in practice. These hypothetical measurement errors can be avoided if the divider is restricted to measurement of applied impulse waves that do not reach crest value until times long compared to the time required for the divider response to die out to its steady-state value.

The oscillatory response noted on many dividers is primarily an oscillation between the terminal capacitance of the divider and the inductance of the line lead short-circuited through the zero impedance of the step voltage generator. Energy is traded back and forth between the inductance and the terminal capacitance. Even if the high voltage arm of the divider had no terminal capacitance, a physically impossible condition, there could be an oscillation set up by virtue of traveling waves on the line lead of the divider. Both the high resistance of the high voltage arm of the divider and the zero impedance of the step voltage generator present discontinuities to waves traveling on the line lead and hence lead to reflections on the divider high voltage lead. The L-C oscillation between the line lead inductance and the divider terminal capacitance is merely the integrated response of many round-trip reflections of traveling waves on the line lead.

In an impulse circuit there may very well be no suitable path for the interchange of energy between the terminal capacitance of the divider and the inductance of the line lead. Thus, a divider system which has an oscillatory response to a step voltage produced by a zero impedance generator may very well not have an oscillatory response when driven by an impulse generator circuit and so may perform quite satisfactorily.

No systematic investigations have been made by the author on the source impedance of actual high voltage impulse generating circuits, but Figure 3 shows the calculated impedance of one hypothetical impulse circuit. This calculated response neglects the effects of inductance or second order capacitances of the circuit. It can be seen that the impedance of this circuit varies considerably with frequency and thus with time. As if to complicate matters further, the impedance of the circuit may change, thus changing the frequency characteristics of the voltage divider. This is the case when a test piece or a rod gap flashes over. On the front of the wave the impedance driving the voltage divider is that of the normal impulse test circuit and may or may not be low enough to allow a divider system to oscillate. However, once the test piece or rod gap flashes over, the divider is effectively connected to a zero impedance source, the zero or low impedance of the flashover path. When and if the IEC addresses itself to the measurement of voltage during the collapsing portion of the flashover, this change of circuit impedance must be considered further. At this stage it should be noted that an impulse measuring circuit which has a satisfactory step function response when excited from a zero impedance step voltage generator will have a satisfactory response when excited from any higher impedance source. The only problem is that the step function response might be better than is necessary, since an impulse measuring system that does not meet the step function requirements may also perform satisfactorily when excited by a conventional impulse circuit. Messrs. Creed (Canada) and Markussen (Norway) have both demonstrated this. They have connected two impulse measuring circuits, one meeting the step function criteria of the IEC and the other not meeting that criteria, in parallel and demonstrated that the two divider systems measured substantially the same voltage.

This leads to the first subject under consideration. If determining the step voltage response of a divider system from a zero impedance generator is too severe a test of the divider, what test can be substituted in its place? Mr. J. H. Park and Mr. F. C. Creed and others have suggested that a sphere gap volt-time curve be used as a transfer standard of voltage, and Mr. Creed has worked out a way of determining divider system response time from measurements made on the standard sphere gap. Mr. Creed has also introduced the concept of the infinite line response of a divider system. In the infinite line response concept the voltage divider system is excited from a transmission line pulse generator having an impedance equal to the impedance of the line lead of the divider. A variant on this theme employs a zero impedance step voltage generator exciting the divider system through a resistance having a value equal to the surge impedance of the line lead of the divider.

I wish to introduce two other possible concepts that might be employed for determining the step function response. Neither of them has been tried in practice to observe their advantages or shortcomings. They are shown on Figure 4. In Figure 4A the load capacitance (or test piece capacitance) is initially disconnected from the impulse circuit but charged to a DC voltage through a high resistance isolating resistor. The gaps of the impulse generator are shorted. The charged load capacitance is then discharged into the generator circuit with its connected divider circuit through the switch. If the performance of the switch has been independently verified, and mercury-wetted contact switches do indeed switch with extremely small time delay, then the effect is as though a step voltage has been injected into the entire circuit. The voltage across the load capacitance does not decay from its initial DC value for times long compared to the response time of any useful voltage divider. This test would have to be made at low voltage and, consequently, the divider output would have to be displayed on an oscilloscope with an amplifier. In Figure 4B an extra capacitance is inserted in series with the load capacitance (or test piece capacitance) circuit. This capacitance would be a value such that when the generator was fired, about 25% of the total output voltage would be developed across C_{L1}. A gap, preferably a pressurized gas gap, would be connected in parallel with C_{L1} and set to spark over at or after the crest of the impulse wave. Thus, a step voltage would again be introduced into the entire circuit with the response of the circuit after the insertion of the voltage being determined by the normal generator and divider circuit since, at that time, C_{L1} would have been shorted. With this concept the step function response voltage from the divider would be large enough that it could be displayed directly on the measuring oscilloscope. The step function response of the divider would then be superimposed on the normal output voltage of the circuit.

A second major shortcoming of the concept of response time itself is shown on Figure 5. It is assumed that the oscillatory responses shown are true oscillatory response of the divider circuit and that generator circuit source impedances have been considered correctly. In Figure 5A the response time determination is straightforward, leading to a response time τ_1. Such a circuit responds to an idealized front chopped wave as shown on Figure 5B, leading to an error voltage E_1.

The system shown on Figure 5C responds in a different way in that there is a very large initial portion of the response time. Such a circuit would have an integrated response time, τ_2, of very large value. This circuit would respond to the idealized front chopped wave as shown on Figure 5D. At the time of chopping the error voltage would be E_2, but the divider response would continue to increase until at its maximum value the difference between the ultimate maximum value of the response and the maximum value of the applied wave had an error voltage, E_3. Thus, most of the response time of the divider of Figure 5C is in effect only a time delay. The IEC document recognizes this situation and says in effect that one should disregard all contributions to the response time prior to time t when the response voltage has only a negligible value. There is a problem, however, in deciding at what time the response is no longer of a negligible value. If the response wave is extrapolated to a virtual zero, the area τ_1 is called the fractional response time.

The concept of response time, I think, has a major defect in that it tries to compress all knowledge about the transient response of a divider system into one single number. One single number is just not sufficient information to describe the transient response of any system, even assuming it is determined correctly, including all problems of source impedance or effective time delays. For instance, the two divider systems on Figure 6 have the same initial rate of rise of the transient response, the same A_1 response time, even though the total response time of the divider of Figure 6B is much less than the response time of 6A. System B will indeed respond in most cases better than System A, but not always. Even if the response time, τ_2, of System B is zero, System B will still not measure all types of waves with zero error. The IEC document recognizes this fact and places restrictions on the type of wave that may be measured with a certain response time, saying in effect that the time to crest of the applied wave must be considerably longer than the time taken for all oscillations of the step response to die out to a negligible value.

Some years ago I wrote a paper in which I applied the concept of rise time to the transient response of impulse divider circuits.[1] In that paper I presented a number of curves relating transient measurement accuracy and the shape of the applied wave to the rise time and the percent overshoot of the step function response. In that paper also the determination of the true step function response was obscured by the use of a zero impedance step voltage generator, but the concepts are still valid provided the true measuring system step function response is determined. A major virtue of the concept of rise time is that it is a true measure of the ability of the measurement circuit to respond to rapidly-changing inputs. For instance, on Figure 5 a measurement of the rise time of the two divider systems would preclude having to make an estimate of the contribution to the response time that was attributable only to a delay in the measurement circuit. Likewise, on Figure 6 a measurement of rise time would indicate that both dividers were limited to about the same extent in their ability to follow a rapidly-changing input, even though the divider of Figure B had a lower response time than that of Figure A. The overshoot and decrement of the step function response are also useful measures of the degree to which the measuring system is able to follow rapidly-changing impulse waves. Both overshoot and decrement may be determined by simple scaling of amplitudes of the response wave while the rise time may be determined by a simple measurement of time between two points on the response wave. All of these parameters do not depend on any sort of integration of the overall response wave and are thus better adapted for determination by people who are not specialists in the impulse measurement arts.

Defining the transient response of a system in terms of rise time, overshoot, and decrement factor is admittedly a more complicated process than defining it in terms of the single parameter response time, but I think it would be better both in theory and in practice if such concepts were used. The major drawback is, of course, that several years effort has been expended by the IEC on the concept of response time and it may not be desirable to attempt something new at this date.

Perhaps the two concepts reinforce each other more than they oppose each other. A statement of rise time would be an important addition to a specification based on response time as it would thus provide a better measure of the divider system response to rapidly-changing waves. Response time is also a useful supplement to a specification based on rise time since the total response time determination tends to include the effect of overshoot and damping of any oscillatory response.

Finally, it might be noted that the concepts of partial response time and settling time that are now under discussion are closely related to the concepts of rise time and decrement factor discussed above.

REFERENCES

1. Fisher, F.A., "Transient Response of Impulse Voltage Dividers", AIEE Transactions, Part I (Communication and Electronics), vol. 77, 1958, pp. 411-420.

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May 12, 1969

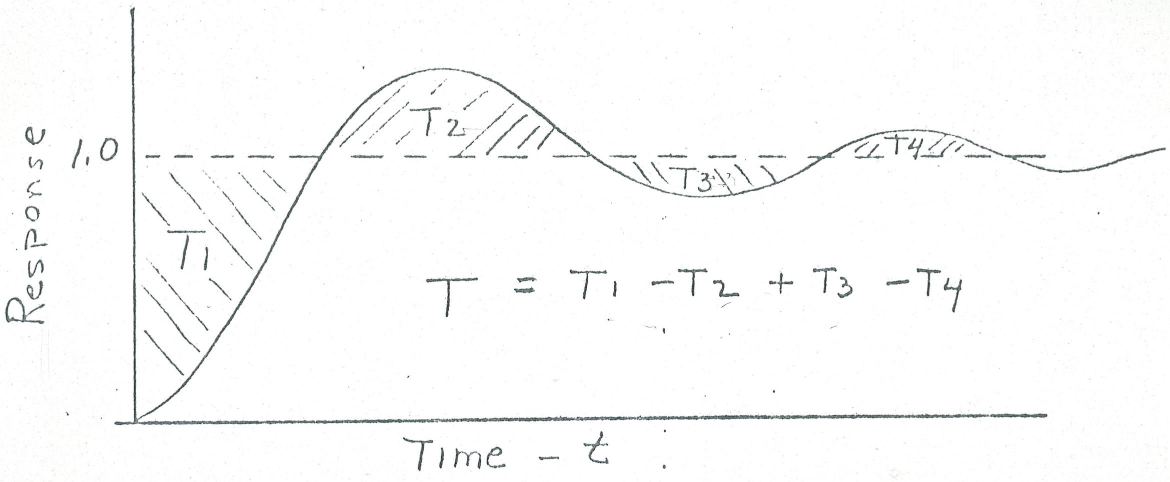


Fig 1

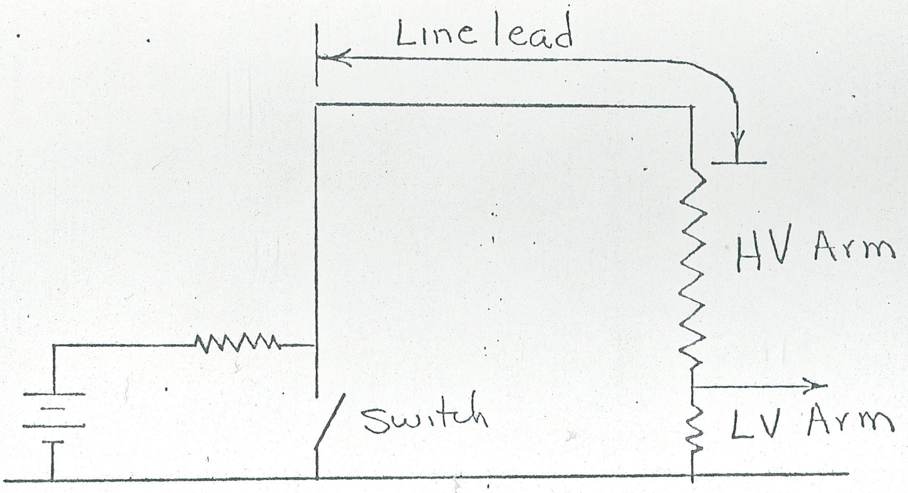

Line lead
HV Arm
Switch
LV Arm

Fig 2A

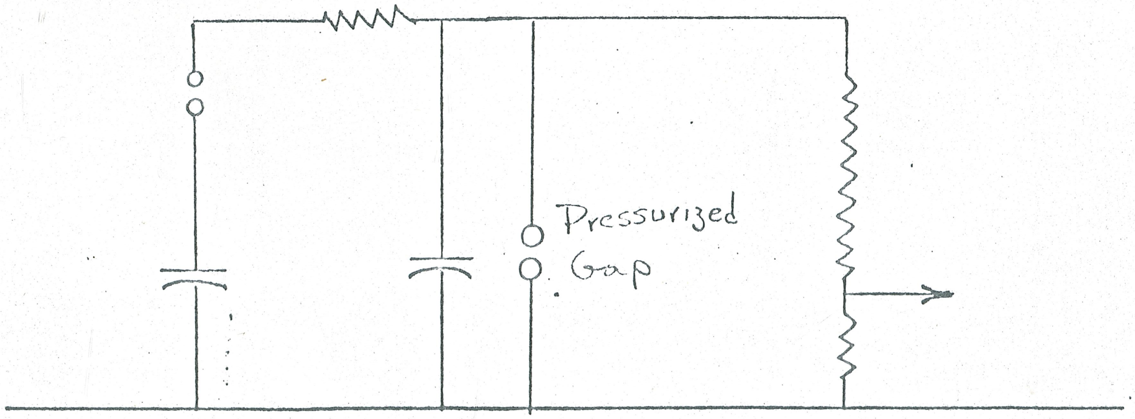

Pressurized
Gap

Fig 2B

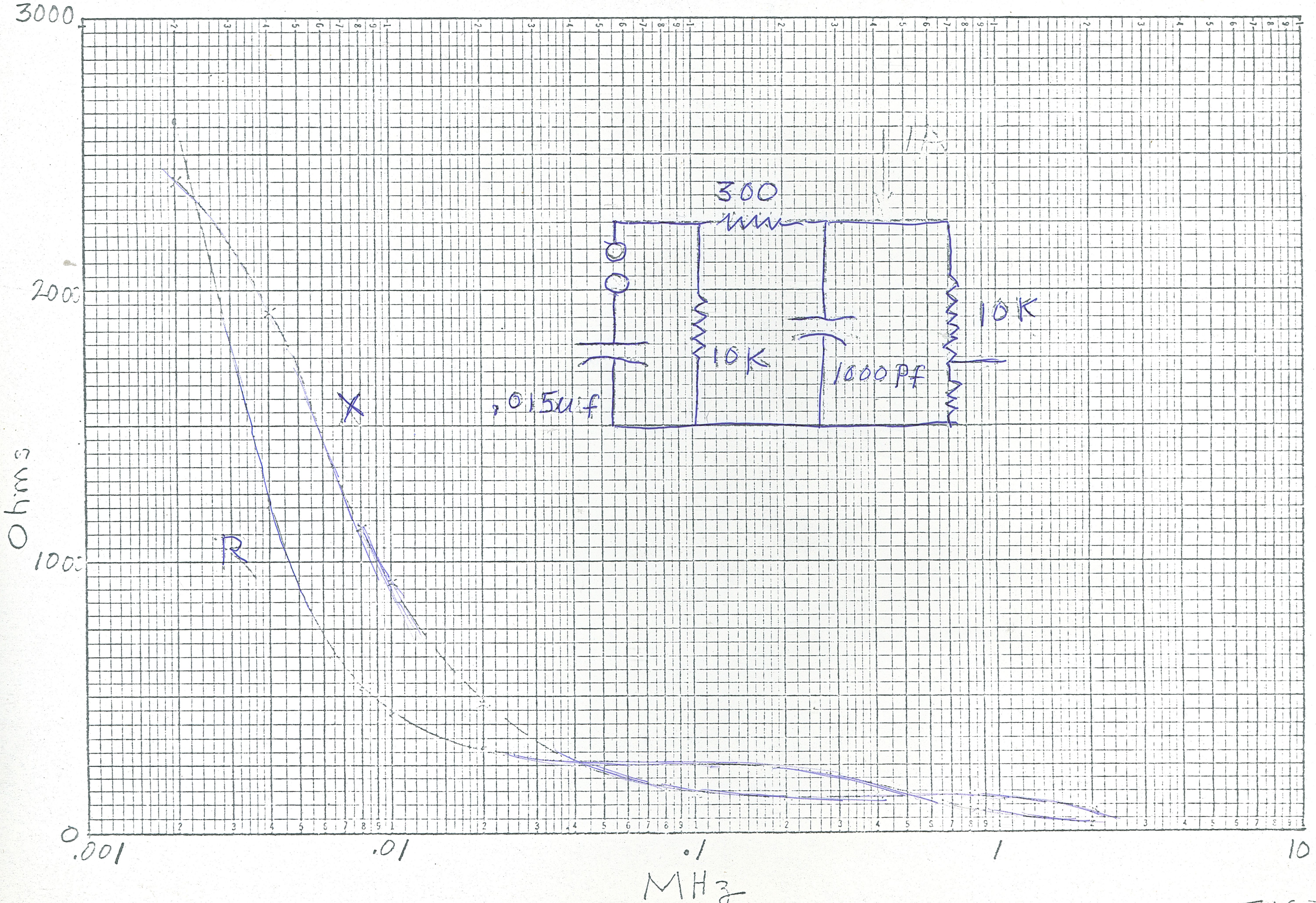

3000
2000
1000
0
Ohms
.001
.01
.1
1
10
MHz
X
R
300
10K
10K
1000pf
,015uf
1A

FIG 5

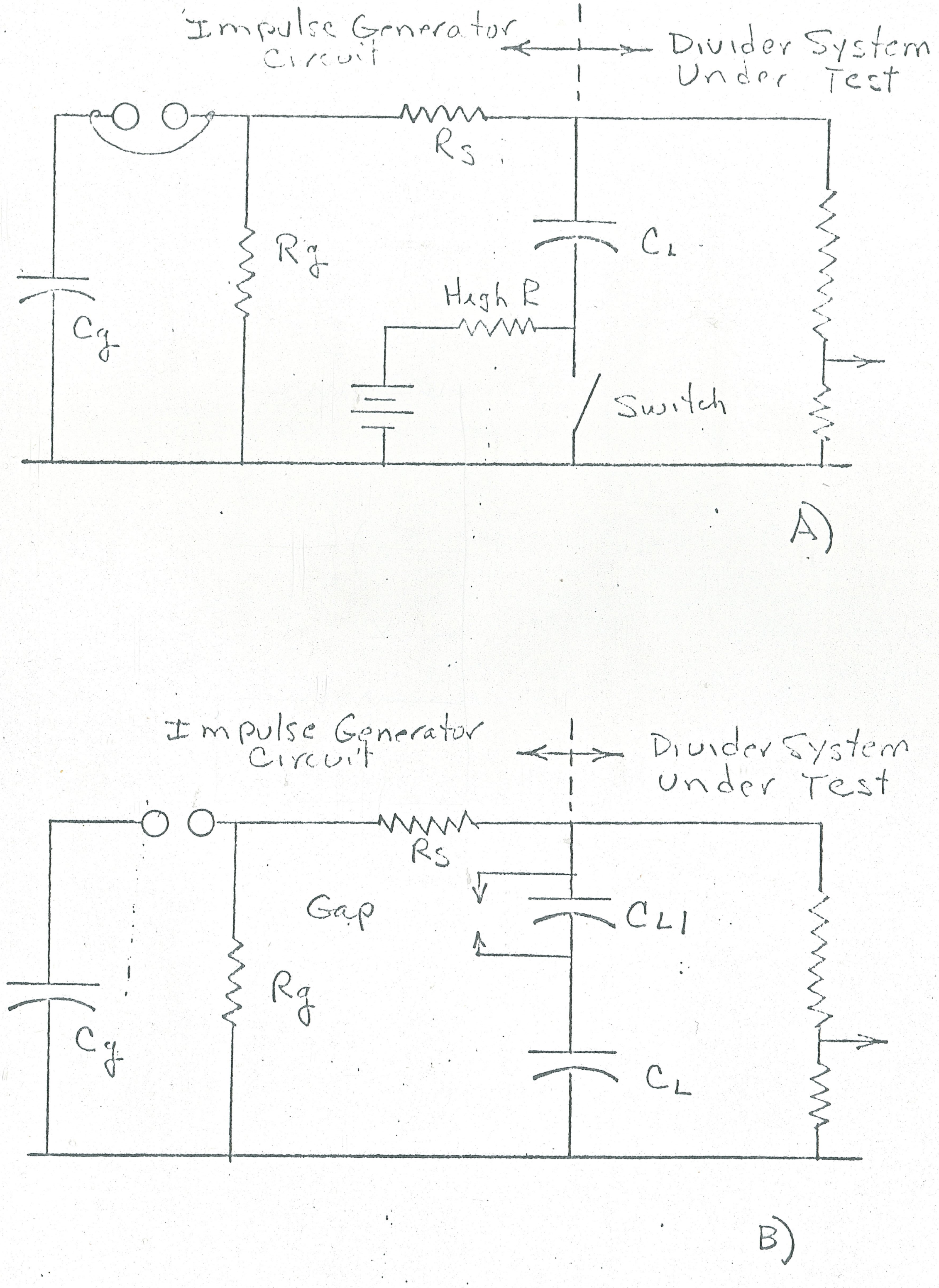
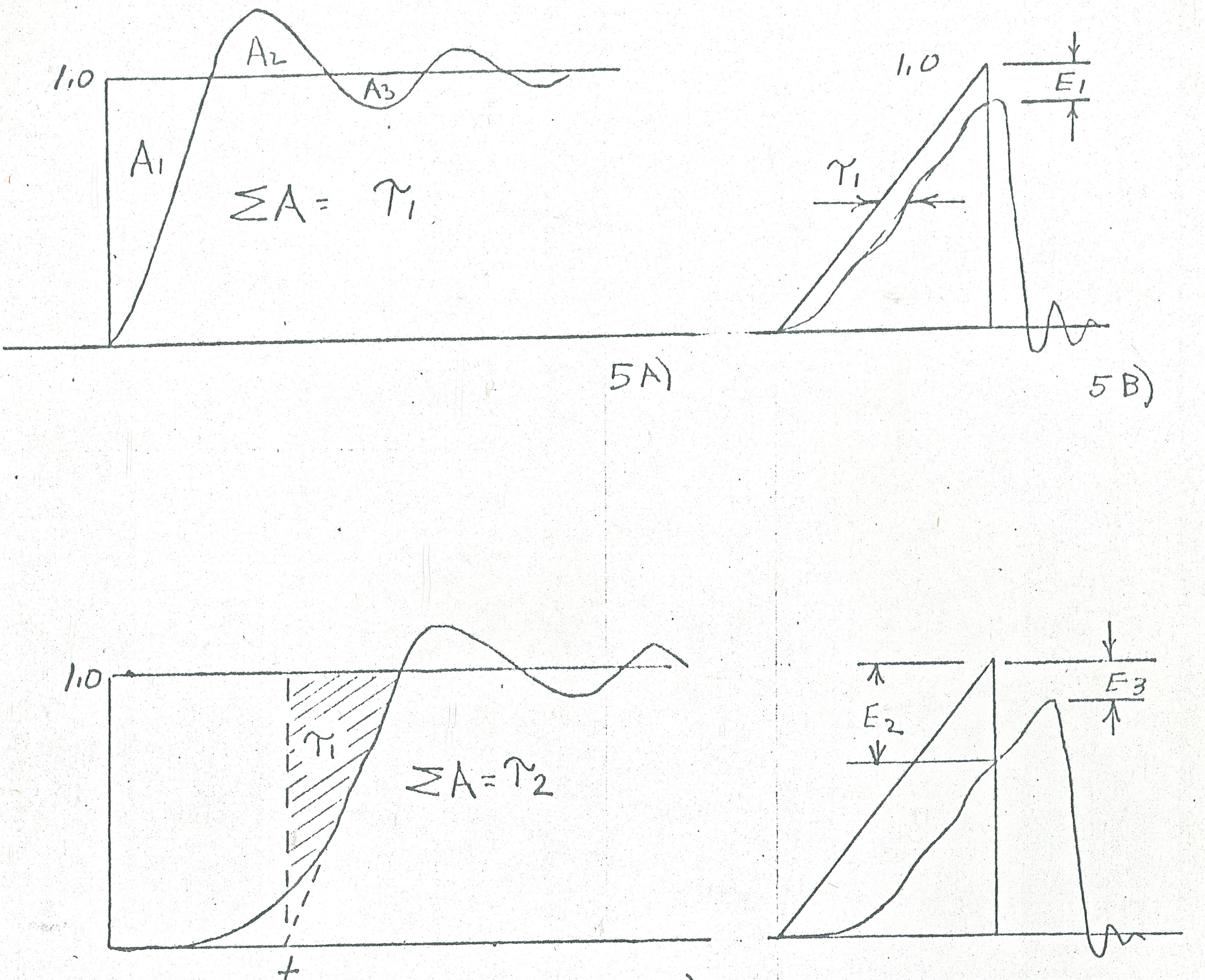

Impulse Generator Circuit
Divider System Under Test
Rs
Rg
Cg
CL
High R
Switch
A)
Impulse Generator Circuit
Divider System Under Test
Rs
Gap
CL1
Rg
Cg
CL
B)

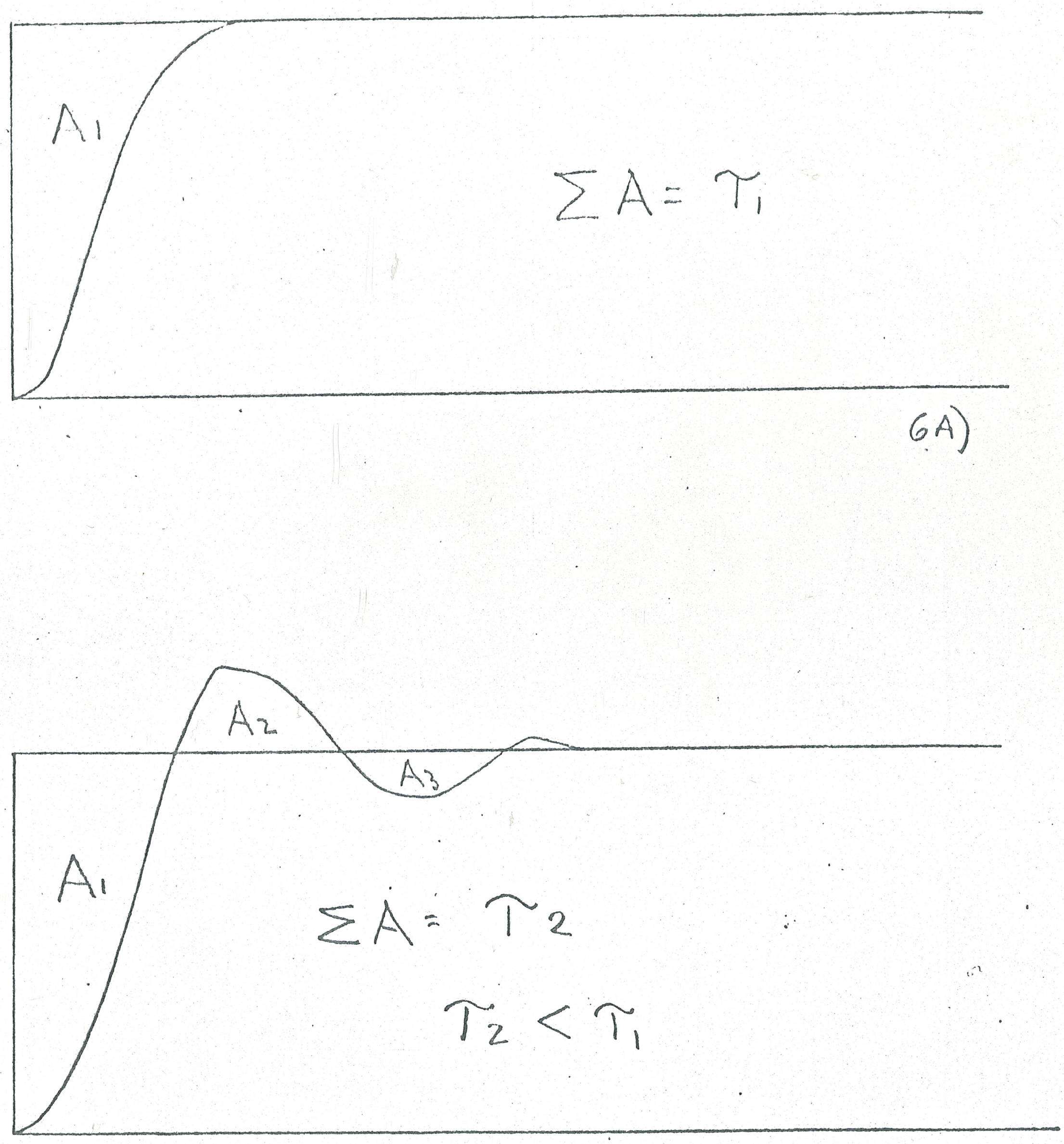
Fig 4


1,0
A1
A2
A3
ΣA = τ1
1,0
E1
τ1
1,0
τ1
ΣA = τ2
t
E2
E3

5A) 5B)

5C) 5D)

FIG-5


A_1
$\Sigma A = \tau_1$
A_2
A_3
A_1
$\Sigma A = \tau_2$
$\tau_2 < \tau_1$

6A)

6B

FIG 6

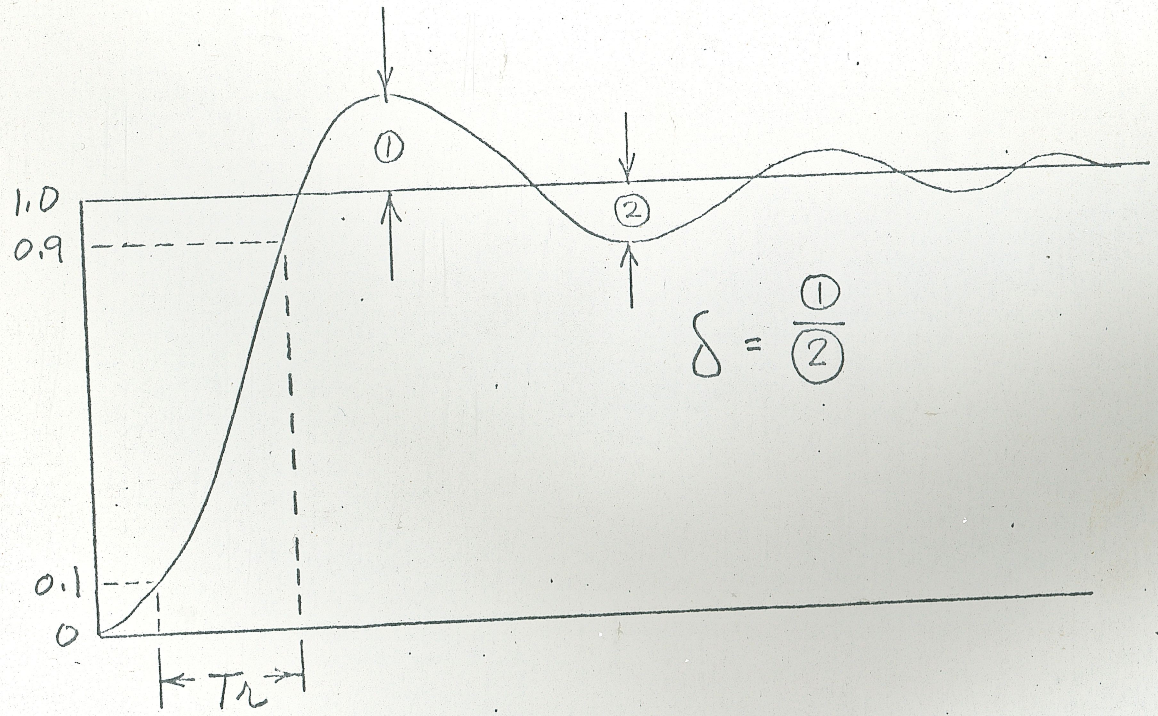


FIG 7